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Constraints on General $SU(2)_L \times SU(2)_R \times U(1)$ Electroweak Models from Nuclear Beta Decay

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1. Introduction

The minimal standard model of the electroweak interactions is consistent with all available data. Nuclear β-decay experiments contribute to this conclusion through the absence of evidence for deviations from the V-A structure of the underlying charged-current quark-lepton interaction [1]. New contributions to the β-decay interaction are expected at some level in many extensions of the minimal standard model, motivated by the problems and the shortcomings of the latter.

An attractive class of extensions of the minimal standard model, which sheds a new light on the apparent V-A structure of the charged-current weak interactions, is the class of left-right symmetric models based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)$ [2]. A characteristic feature of these models is the presence of right-handed charged currents. Among the sensitive probes of right-handed currents are some observables in nuclear beta decay. Except for the time-reversal odd correlation [3,4] $\langle\vec{J}\rangle\cdot\vec{p}_e\times\vec{p}_\nu$ ($\vec{J}$ ≡ nuclear spin) and some preliminary remarks on $e^\pm$ polarization [4], the implications of the corresponding measurements have been considered [5-9] so far only for models with manifest left-right symmetry [5] and no mixing in the leptonic sector. Here we shall analyze the implications of beta-decay experiments for more general versions of $SU(2)_L \times SU(2)_R \times U(1)$ models, including the most general one which allows for CP-violation, unequal left- and right-handed quark mixing angles, and mixing in the leptonic sector. For each scenario we shall compare the constraints on the pertinent parameters from beta-decay measurements with the constraints provided on them by other data.

2. The Beta-Decay Interaction in $SU(2)_L \times SU(2)_R \times U(1)$ Models

In $SU(2)_L \times SU(2)_R \times U(1)$ models there are two distinct charged gauge boson fields W_L and W_R. Their coupling to the fermions is described by the Lagrangian*

$$L = \frac{g_L}{2\sqrt{2}} W_L (\bar{P}\Gamma_L U_L N + \bar{N}^{(0)}\Gamma_L U^\dagger E) + \frac{g_R}{2\sqrt{2}} W_R (\bar{P}\Gamma_R U_R N + \bar{N}^{(0)}\Gamma_R V^\dagger E) + \text{H.c.} \quad , \tag{2.1}$$

where g_L and g_R are the gauge coupling constants, $\Gamma_L \equiv \gamma_\lambda(1-\gamma_5)$, $\Gamma_R \equiv \gamma_\lambda(1+\gamma_5)$ (the Dirac indices have been suppressed), $\bar{P} \equiv (\bar{u},\bar{c},\ldots)$, $\bar{N} \equiv (\bar{d},\bar{s},\ldots)$, $\bar{E} \equiv (\bar{e},\bar{\mu},\ldots)$, and $\bar{N}^{(0)} \equiv (\bar{\nu}_1,\bar{\nu}_2,\ldots)$. U_L, U_R and U, V are the quark and lepton mixing matrices, respectively. The fields W_L and W_R are linear combinations of the mass-eigenstates W_1 and W_2

$$W_L = \cos\zeta W_1 + \sin\zeta W_2$$
$$W_R = e^{i\omega}(-\sin\zeta W_1 + \cos\zeta W_2) \quad , \tag{2.2}$$

where ζ is a mixing angle and ω is a CP-violating phase.

The Hamiltonian responsible for nuclear beta decay resulting from (2.1) is given by

*A brief review of the relevant aspects of $SU(2)_L \times SU(2)_R \times U(1)$ is contained in Ref. 10.

$$H^{(\beta)} = a_{LL}[\bar{e}\Gamma_L \nu_e^{(L)}\, \bar{u}\Gamma_L d + \eta_{RR}\bar{e}\Gamma_R \nu_e^{(R)}\, \bar{u}\Gamma_R d + \eta_{LR}\bar{e}\Gamma_L \nu_e^{(L)}\, \bar{u}\Gamma_R d + \eta_{RL}\bar{e}\Gamma_R \nu_e^{(R)}\, \bar{u}\Gamma_L d] + \mathrm{H.c.} \quad , \tag{2.3}$$

where $\nu_e^{(L)} = \Sigma_j U_{ej}\nu_j$, $\nu_e^{(R)} = \Sigma_j V_{ej}\nu_j$. Assuming that m_1^2/m_2^2 can be neglected relative to one and that $\tan^2\zeta$ can be neglected relative to m_1^2/m_2^2, the constants a_{LL}, η_{RR}, η_{LR}, and η_{RL} are given by

$$\begin{aligned} a_{LL} &= g_L^2\cos^2\zeta/8m_1^2 \\ \eta_{RR} &= e^{i\alpha}(g_R^2 m_1^2/g_L^2 m_2^2)\cos\theta_1^R/\cos\theta_1^L \\ \eta_{LR} &= -e^{i(\alpha+\omega)}(\cos\theta_1^R/\cos\theta_1^L)(g_R\tan\zeta/g_L) \\ \eta_{RL} &= -e^{-i\omega}g_R\tan\zeta/g_L \quad , \end{aligned} \tag{2.4}$$

where m_1, m_2 are the masses of W_1, W_2, and α is a CP-violating phase from U_R ($U_{ud}^L = \cos\theta_1^L$, $U_{ud}^R = e^{i\alpha}\cos\theta_1^R$).

A Hamiltonian of the form (2.3) with arbitrary constants would be determined by seven real parameters (four complex numbers minus an overall phase). In $SU(2)_L \times SU(2)_R \times U(1)$ models the number of independent parameters is six, in view of the relation $\eta_{RR}\eta_{RL}^*/|\eta_{RR}||\eta_{RL}| = \eta_{LR}/|\eta_{LR}|$. One of these, associated with an interference term between left-handed and right-handed leptonic currents, can appear only through contributions proportional to the neutrino masses and will be ignored in the following. As the neutrinos are not detected, the observed β-decay probability is a sum of the probabilities of decays into energetically allowed neutrino mass-eigenstates. We shall assume in the following that the effects of the masses of the neutrinos that can be produced in the decay can be neglected. Taking all the above into account, the following six parameters are available in β-decay: $a_{LL}^{(e)} \equiv a_{LL}\sqrt{u_e}$, $|\eta_{RR}^{(e)}| \equiv |\eta_{RR}|\sqrt{\tilde{v}_e}$, $|\eta_{LR}|$, $|\eta_{RL}^{(e)}| \equiv |\eta_{RL}\sqrt{\tilde{v}_e}|$, η_{LR} and $\eta_{RR}^{(e)}\eta_{RL}^{(e)*}$, where $u_e = \Sigma_i' |U_{ei}|^2$, $v_e = \Sigma_i' |V_{ei}|^2$, $\tilde{v}_e = v_e/u_e$; the summation is over the neutrino states produced in the decay. Only five of the above parameters are independent, due to the mentioned relation.

For a measurement to yield significant constraints on new interactions the expression for the chosen observable must be free of quantities with large theoretical uncertainties or experimental errors. This restricts the choice to allowed decays. With the exception of the coefficient of the T-odd correlation $\langle\vec{J}\rangle\cdot\vec{p}_e\times\vec{p}_\nu/E_eE_\nu$ (D-coefficient) we shall consider from these only pure transitions, since generally the ratio of the Gamow-Teller and Fermi matrix elements is not known with sufficient accuracy (an exception is neutron decay,* where the matrix elements are known exactly, and which provides the value of the axial-vector coupling constant g_A). For the D-coefficient, which vanishes (up to electromagnetic final-state effects) in the minimal standard model, the precise knowledge of the nuclear matrix elements is not essential.

The parameter $a_{LL}^{(e)}$ appears only in the decay rate (in the $O^{14} \to N^{14*}e^+\nu$ superallowed Fermi transition it is involved in the combination of parameters which define $G\cos\theta_c$, where G is the μ-decay coupling constant). The normalized spectrum depends only on the η_{ik}'s. In pure transitions (ignoring recoil-order terms, higher-forbidden contributions and electromagnetic effects) all the observables (except for the rates) are either independent of the η_{ik}'s or proportional to the quantities

$$x_V = \frac{|1 + \eta_{LR}|^2 - |\eta_{RR}^{(e)} + \eta_{RL}^{(e)}|^2}{|1 + \eta_{LR}|^2 + |\eta_{RR}^{(e)} + \eta_{RL}^{(e)}|^2} \simeq 1 - 2|\eta_{RR}^{(e)} + \eta_{RL}^{(e)}|^2 \quad \text{(Fermi transitions)} \tag{2.5}$$

and

*Another case is ^{19}Ne-decay (see B. R. Holstein and S. B. Treiman, Ref. 6), where constraints can be obtained on manifestly symmetric $SU(2)_L \times SU(2)_R \times U(1)$ models by eliminating the unknown matrix elements using other data.

$$x_A = \frac{|1-\eta_{LR}|^2 - |\eta_{RR}^{(e)} - \eta_{RL}^{(e)}|^2}{|1-\eta_{LR}|^2 + |\eta_{RR}^{(e)} - \eta_{RL}^{(e)}|^2} \approx 1 - 2|\eta_{RR}^{(e)} - \eta_{RL}^{(e)}|^2 \quad \text{. (Gamow-Teller transitions)} \qquad (2.6)$$

In both cases they are independent of the nuclear matrix elements. It follows that information can be obtained only on the parameters $|\eta_{RR}^{(e)}|$, $|\eta_{RL}^{(e)}|$, and $\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}$. In addition, the D-coefficient provides information on $\mathrm{Im}(\eta_{LR} + \eta_{RR}^{(e)}\eta_{RL}^{(e)*})$. CT-conserving observables in mixed transitions would be generally sensitive also to $\mathrm{Re}\,\eta_{LR}$ and $|\eta_{LR}|$.

3. Constraints from Beta-Decay Measurements

The average value of x_A from experimental results on Gamow-Teller transitions is [7]

$$(x_A)_{expt} = 1.001 \pm 0.012 \quad . \qquad (3.1)$$

A recent accurate measurement of the positron longitudinal polarization in a Fermi transition ($P_e^F = x_V$) yielded [9]

$$(x_V)_{expt} = 0.99 \pm 0.04 \quad . \qquad (3.2)$$

An approach followed in recent and in ongoing experiments [11] involves a comparison of positron longitudinal polarizations (P_e^F, P_e^{GT}) in a Fermi and a Gamow-Teller transition for positrons of the same energy.* The present experimental result on P_e^F/P_e^{GT} is [9]

$$(P_e^F/P_e^{GT})_{expt} = 0.986 \pm 0.038 \quad . \qquad (3.3)$$

The accuracy for $(P_e^F/P_e^{GT})_{expt}$ is expected to be improved by 1-2 orders of magnitude [11].

The experimental value of the D-coefficient from a recent experiment [13], which has the smallest error, is

$$(D)_{expt} = 0.0004 \pm 0.0008 \quad . \qquad (3.4)$$

The results (3.1) and (3.2) imply at 90% confidence level $|\eta_{RR}^{(e)} - \eta_{RL}^{(e)}| < 0.085$ and $|\eta_{RR}^{(e)} + \eta_{RL}^{(e)}| < 0.18$, yielding the bounds

$$|\eta_{RR}^{(e)}| < 0.13 \quad \text{for any } |\eta_{RL}^{(e)}| \text{ and } \cos(\alpha + \omega) \quad , \qquad (3.5)$$

$$|\eta_{RL}^{(e)}| < 0.13 \quad \text{for any } |\eta_{RR}^{(e)}| \text{ and } \cos(\alpha + \omega) \quad . \qquad (3.6)$$

The result (3.3) implies the limit [note that $(1-P^F/P^{GT})/8 \approx \mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}$]

$$|\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}| < 10^{-2} \quad (90\%\ \text{confidence}). \qquad (3.7)$$

A slightly better limit ($|\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}| < 8 \times 10^{-3}$) follows from (3.1) and (3.2).

The D-coefficient has been discussed previously in Refs. 3 and 4. Barring a cancellation, the result (3.4) sets the constraints**

$$|\mathrm{Im}\,\eta_{LR}| \lesssim 2 \times 10^{-3} \qquad (3.8)$$

$$|\mathrm{Im}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}| \lesssim 2 \times 10^{-3} \quad . \qquad (3.9)$$

4. Constraints on the Beta-Decay Parameters from Other Sources

Among other data the most stringent constraints on the parameters of $SU(2)_L \times SU(2)_R \times U(1)$ models come from muon-decay measurements, and from data which include some nonleptonic transitions. It should be noted that the latter are less reliable, in view of the uncertainties in calculations of nonleptonic

*A brief account of the conclusions regarding P_e^F/P_e^{GT} reported here is given in Ref. 12.

**We note that $|\mathrm{Im}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}| < |\mathrm{Im}\,\eta_{LR}|$, provided that $g_R^2 m_1^2/g_L^2 m_2^2 < 1$.

amplitudes. The implications of muon-decay data on the β-decay parameters depend on whether $\tilde{v}_\mu$ is arbitrary or $\tilde{v}_\mu = 1$.* We shall consider three classes of models, distinguished by the values of $\tilde{v}_\mu$ and $\tilde{v}_e$.

(A) Models with $\tilde{v}_e = \tilde{v}_\mu = 1$. Examples are models where U = V (such as $SU(2)_L \times SU(2)_R \times U(1)$ models with Dirac neutrinos and a discrete left-right symmetry). $\tilde{v}_e = \tilde{v}_\mu = 1$ also if all the neutrinos are sufficiently light to be produced in β-decay.

Constraints from μ-decay.** The μ-decay Hamiltonian resulting from (2.1) is given by

$$H^{(\mu)} = c_{LL}[\bar{e}\Gamma_L\nu_e^{(L)}\bar{\nu}_\mu^{(L)}\Gamma_L\mu + \kappa_{RR}\bar{e}\Gamma_R\bar{\nu}_\mu^{(R)}\Gamma_R\mu + \kappa_{LR}\bar{e}\Gamma_L\nu_e^{(L)}\bar{\nu}_\mu^{(R)}\Gamma_R\mu + \kappa_{RL}\bar{e}\Gamma_R\nu_e^{(R)}\bar{\nu}_\mu^{(L)}\Gamma_L\mu] + \text{H.c.} \quad , \tag{4.1}$$

where $\nu_\mu^{(L),(R)}$ are defined as $\nu_e^{(L),(R)}$ except for $e \to \mu$, and $c_{LL} = a_{LL}/\cos\theta_1^L$, $\kappa_{RR} = \eta_{RR}(\cos\theta_1^L/\cos\theta_1^R)e^{-i\alpha}$, $\kappa_{LR} = e^{-i\alpha}\eta_{LR}(\cos\theta_1^L/\cos\theta_1^R)$, and $\kappa_{RL} = \eta_{RL}$.

Since $|\cos\theta_1^R/\cos\theta_1^L| \lesssim 1$, we have $|\eta_{RR}| \lesssim |\kappa_{RR}|$ and $|\eta_{LR}| \lesssim |\eta_{RL}| = |\kappa_{RL}| = |\kappa_{LR}|$. The best limit on $|\kappa_{RR}|$ from leptonic and semileptonic processes comes from the quantity $R = 1 - \delta\xi P_\mu/\rho$, (δ, ξ, and ρ are the usual muon spectrum parameters), related to the end point of the positron spectrum in polarized muon decay. The present experimental limit implies $|\kappa_{RR}| < 0.039$, and therefore

$$|\eta_{RR}^{(e)}| = |\eta_{RR}| \lesssim 0.039 \quad . \tag{4.2}$$

The best limit on $|\kappa_{RL}|$ is provided by the experimental value of the ρ-parameter, implying $|\kappa_{RL}| < 0.033$, so that

$$|\eta_{RL}^{(e)}| = |\eta_{RL}| < 0.033 \quad , \tag{4.3}$$

$$|\eta_{LR}| \lesssim 0.033 \quad . \tag{4.4}$$

The bounds (4.2) and (4.3) are to be compared with the constraints (3.5) and (3.6) obtained from β-decay data. For $|\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}|$ the bounds (4.2) and (4.3) imply***

$$|\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}| \lesssim 1.3 \times 10^{-3} \quad , \tag{4.5}$$

to be compared with the bound (3.7) resulting from the direct measurement.

Constraints from information involving nonleptonic transitions. In models where $\theta_1^R = \theta_1^L$ and there is no CP-violation (models with "manifest left-right symmetry" [5]) the K_L–K_S mass difference Δm_K sets a limit [14]

$$|\eta_{RR}^{(e)}| = |\eta_{RR}| = m_1^2/m_2^2 \lesssim 3 \times 10^{-3} \tag{4.6}$$

on $|\eta_{RR}^{(e)}|$ (we have set $g_R = g_L$ as appropriate for such models), and an analysis of nonleptonic K-decays yields [15]

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*u_μ, v_μ, are defined as u_e, v_e, except for $e \to \mu$; $\tilde{v}_\mu \equiv v_\mu/u_\mu$.

**A study of the implications for general $SU(2)_L \times SU(2)_R \times U(1)$ models of measurements of the positron momentum spectrum end point in polarized μ-decay, which we use here, is given in Ref. 10.

***Inspection shows that the constraint $|\eta_{LR}| < 0.033$ improves the bound on κ_{RR} from R only slightly.

$$|\eta_{LR}| = |\zeta| \lesssim 4 \times 10^{-3} \quad . \tag{4.7}$$

If CP-violation is present in the nonleptonic sector, but still $\theta_1^R = \theta_1^L$ (so-called "pseudomanifest left-right symmetry"), the limit from Δm_K and the CP-violating parameter ε imply again the bound (4.6) [3,16]. The bound (4.7) is also recovered, combining the limit from nonleptonic K-decays [now proportional to $\cos(\alpha + \omega)$] with the limit (3.7) [proportional to $\sin(\alpha + \omega)$] (see Ref. 10). From (4.6) and (4.7) one obtains the stringent bound

$$|\mathrm{Re}\,\eta_{RR}^{(e)*}\eta_{RL}^{(e)*}| \lesssim 2 \times 10^{-5} \quad . \tag{4.8}$$

For models where θ_1^R and θ_1^L are unrelated, the $K^0 \to \bar{K}^0$ amplitude sets no constraints on η_{RR} or κ_{RR} (see Ref. 10). The constraints from nonleptonic K-decays and the D-coefficient takes the form

$$|\eta_{LR}| = |g_R\zeta\cos\theta_1^R/g_L\cos\theta_1^L| \lesssim 4 \times 10^{-3} \quad . \tag{4.9}$$

Observing that $\eta_{RR}\eta_{RL}^* = \kappa_{RR}\eta_{LR}$, we obtain from the limit on $|\kappa_{RR}|$ from R and from (4.9) the bound

$$|\mathrm{Re}\,\eta_{RR}\eta_{RL}^*| \lesssim 2 \times 10^{-4} \quad . \tag{4.10}$$

$|\mathrm{Im}\,\eta_{LR}|$ is constrained by the CP-violating parameter ε' in $K_L \to 2\pi$ decays, and also by the electric dipole moment of the neutron (D_n) to be less than $\sim 10^{-4}$ [4]. These constraints are, of course, less reliable than the constraints (3.8) from the direct measurement.

(B) Models with arbitrary $\tilde{v}_e$ and $\tilde{v}_\mu$. In this case muon decay does not provide a constraint on $\eta_{RR}^{(e)}$. The ρ-parameter yields

$$|\eta_{RL}^{(e)}| < 0.047 \quad \text{(90\% confidence)}, \tag{4.11}$$

which is the best limit on $|\eta_{RL}^{(e)}|$ from leptonic and semileptonic data. Combining (4.11) with the bound $|\eta_{RR}^{(e)} - \eta_{RL}^{(e)}| < 0.085$ from data on Gamow-Teller β-decays (3.1) yields

$$|\eta_{RR}^{(e)}| < 0.12 \tag{4.12}$$

i.e., the same limit as from x_V and x_A (3.5). The limits (4.11) and (4.12) imply

$$|\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}| < 6 \times 10^{-3} \quad . \tag{4.13}$$

We note that here a bound on $\eta_{RL}^{(e)}$ does not imply a bound on $|\eta_{LR}|$. The best limit on $|\eta_{LR}|$ in this case from leptonic and semileptonic processes is $|\eta_{LR}| < 0.1$ provided by data on inclusive neutrino and antineutrino scattering [17].

Since $\tilde{v}_e \lesssim 1$ (see Ref. 10), for models with manifest or pseudomanifest left-right symmetry the limits (4.6) and (4.7) hold for $|\eta_{RR}^{(e)}|$ and $|\eta_{LR}|$, implying the bound (4.8), as for models of class (A). In models where θ_1^R and θ_1^L are unrelated only the limit (4.9) from nonleptonic K-decays and the D-coefficient holds. The implication for $\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}$ is

$$|\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}| \lesssim 4 \times 10^{-3} \quad , \tag{4.14}$$

provided that $g_R^2 m_1^2/g_L^2 m_2^2 < 1$ (since $|\eta_{RR}^{(e)}\eta_{RL}^{(e)*}| = |\kappa_{RR}\sqrt{\tilde{v}_e}\eta_{LR}/\sqrt{\tilde{v}_e}| \lesssim |\kappa_{RR}||\eta_{LR}|$). The limits on $|\mathrm{Im}\,\eta_{LR}|$ from ε' and D_n are, of course, the same as in class (A).

(C) Models with $\tilde{v}_\mu = 1$, and arbitrary $\tilde{v}_e$. This scenario would arise if all the neutrinos could be produced in μ-decay but not in β-decay. The conclusions regarding the limits on the beta-decay parameters from other sources are the same as for class (A), except for that, as in class (B) $|\eta_{LR}|$ is not bounded by a limit on $|\eta_{RL}^{(e)}|$.

5. Conclusions

Excluding from consideration mixed transitions and not counting the parameter involved only in the decay rates, β-decay measurements are sensitive to three combinations of parameters of $SU(2)_L \times SU(2)_R \times U(1)$ models: the constants $|\eta_{RR}^{(e)}|$, $|\eta_{RL}^{(e)}|$, and $\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}$.

In $SU(2)_L \times SU(2)_R \times U(1)$ models where $\tilde{v}_\mu = 1$ the available muon-decay data set more stringent limits on the β-decay parameters than the existing β-decay measurements. In particular, the upper limit from muon decay data on the parameter $|\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}|$ (which is measured by the ratio P_e^F/P_e^{GT} of beta-ray polarizations) is smaller by an order of magnitude than the limit from the existing direct measurement. The limit on $|\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}|$ derived from data involving nonleptonic processes is better than the limit from μ-decay data by an order of magnitude.

In $SU(2)_L \times SU(2)_R \times U(1)$ models where $\tilde{v}_\mu$ is arbitrary $|\eta_{RR}^{(e)}|$ is not constrained if beta decay data are not included. The best limit on $|\mathrm{Re}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}|$ from leptonic and semileptonic processes (obtained by combining the information from the ρ-parameter and Gamow-Teller β-decay data), as well as the limit from data involving nonleptonic processes are only slightly better than the present limit from a direct measurement.

In all models where $\theta_1^R = \theta_1^L$ the constraints on the β-decay parameters derived from nonleptonic processes are much more stringent than those implied by other data.

Searches for a nonzero D-coefficient provide constraints on $\mathrm{Im}\,\eta_{LR}$ and $\mathrm{Im}\,\eta_{RR}^{(e)}\eta_{RL}^{(e)*}$. The best limits on these from leptonic and semileptonic processes come from the direct measurement. The constraints derived from nonleptonic processes are more stringent by an order of magnitude, but less reliable.

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References

[1] A. I. Boothroyd, J. Markey, and P. Vogel, Phys. Rev. C29, 603 (1984).

[2] J. C. Pati and A. Salam, Phys. Rev. Lett. 31, 661 (1973), Phys. Rev. D10, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D11, 566, 2558 (1975); G. Senjanovic and R. Mohapatra, Phys. Rev. D12, 1502 (1975).

[3] P. Herczeg, Phys. Rev. D28, 200 (1983).

[4] P. Herczeg, in Neutrino Mass and Low-Energy Weak Interactions, Telemark 1984, ed. by V. Barger and D. Cline, World Scientific Publishing Co., 1985 p. 288.

[5] M. A. Bég et al., Phys. Rev. Lett. 38, 1252 (1977).

[6] B. R. Holstein and S. B. Treiman, Phys. Rev. D16, 2369 (1977).

[7] J. van Klinken, F. W. J. Kobs, and H. Behrens, Phys. Lett. 79B, 199 (1978).

[8] M. Skalsey et al., Phys. Rev. Lett. 49, 708 (1982).

[9] J. van Klinken et al., Phys. Rev. Lett. 50, 94 (1983).

[10] P. Herczeg, "On Muon Decay in Left-Right Symmetric Electroweak Models," Los Alamos National Laboratory preprint LA-UR-85-2761, to be published.

[11] A. Rich and M. Skalsey, private communication; J. van Klinken et al., Phys. Rev. Lett. 50, 94 (1983); J. Deutsch, private communication, and in these Proceedings; see also Ref. 8.

[12] P. Herczeg, in Proceedings of the Second Conference on the Intersections Between Particle and Nuclear Physics, Lake Louise, Canada, May 26-31, 1986. To be published by the AIP.

[13] A. L. Hallin et al., Phys. Rev. Lett. 52, 337 (1984).

[14] G. Beall, M. Bander, and A. Soni, Phys. Rev. Lett. 48, 848 (1982).

[15] J. F. Donoghue and B. R. Holstein, Phys. Lett. 113B, 382 (1982).

[16] H. Harari and M. Leuver, Nucl. Phys. B233, 221 (1984).

[17] H. Abramowicz et al., Z. Phys. C12, 255 (1982).

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